# Estimating afterload, systemic vascular resistance and pulmonary vascular resistance in an intensive care setting

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**Abstract:** Poor management and delayed diagnosis for both pulmonary embolism and septic shock are common and lead to increased cost, length of stay and mortality. Despite a wealth of information coming from commonly placed catheters much of this information remains unknown to an intensive care clinician. Data was gather from two porcine trials, 5 subjects induced with pulmonary embolism, and 5 with septic shock (treated with haemofiltration). Methods for real-time estimating afterload, systemic vascular resistance and pulmonary vascular resistance are presented. Knowledge of these parameters would greatly increase management of patients with pulmonary embolism and septic shock, and help the accuracy and speed of diagnosis. All estimations tracked trends very well. The estimating for afterload has a percentage error of 21.6% in pulmonary embolism and 11.8% in septic shock, systemic vascular resistance has a percentage error of 12.51% and 13.5% for pulmonary embolism and septic shock respectively while pulmonary vascular resistance showed percentage errors of 12.2% and 44.5%. From these estimations, the drop in systemic vascular resistance and afterload can be clearly identified in the septic shock cohort, as well as the recovery after haemofiltration was started, while the pulmonary embolism cohort showed the expected increase in pulmonary vascular resistance.

*Keywords:* Diagnosis, Physiological models, Tracking characteristics, Medical systems, Medical applications, Signal analysis, Identification algorithms

## 1. INTRODUCTION

Cardiac dysfunction is difficult to diagnose in critical care, and often results in inadequate diagnosis or poor management (Guyton and Hall (2000); Grenvik et al. (1989)). This leads to increased length of stay, cost and mortality (Angus et al. (2001); Kearon (2003); Pineda et al. (2001)). Currently in critical care, the amount of usable data available to the clinician is severely limited by the ability to understand the information that is hidden in collected data. As a result, catheters placed around the heart are not necessarily associated with improved outcomes (Frazier and Skinner (2008); Chatterjee (2009); Cooper and Doig (1996)) despite the wealth of information they contain.

Acute cardiovascular dysfunction like pulmonary embolism (PE) and septic shock severely alter the cardiovascular system (CVS) hemodynamics around the heart. These changes can be seen by catheters placed around the heart as changes in pressure and flow. These changes reflect the dynamic changes in the balance of pre-load and afterload, indicating an altered cardiac energetic state (Weber and Janicki (1979); Ross (1976)). However, much of the meaning of this data is lost as the pressure waveforms need processing and or modelling to extract this information, and these energetic metrics and far to invasive to measure directly.

If more of the cardiac energetic metrics could be captured from the catheters already present in an ICU setting, the catheters clinical potential could be realised. This paper presents a method to estimate three of these metrics, afterload, systemic vascular resistance ($R_{sys}$) and the pulmonary vascular resistance ($R_{pul}$). These three metrics are useful in the diagnosis of pulmonary embolism (in which the $R_{pul}$ increases, and for septic shock $R_{sys}$ commonly decreases and is linked to a decrease in afterload. Being able to track these two metrics in real time at the bedside would give valuable non additionally invasive information to the clinician, and potentially decrease the time to diagnosis, increase the reliability of that diagnosis and ultimately improve patient outcomes through better management.

## 2. METHODS

The overall approach in this research was to gather as much information as possible from the time varying cardiac elastance approximation and the aortic pressure waveform, that would give more information about the current

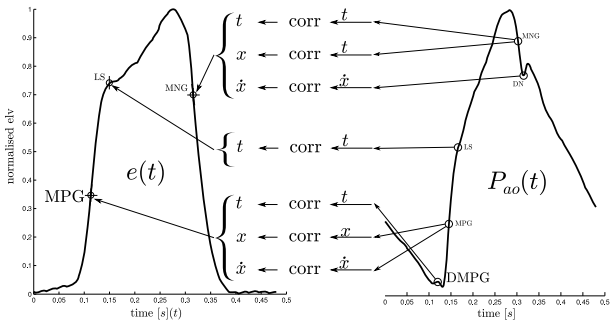


Fig. 1. The left cardiac elastance ($e_{lv}$) and $P_{ao}$ showing the relationship between them and specific points on both waveforms

cardiac dysfunction of the patient. The study was conducted on data taken from a cohort of 9 porcine subjects. These 9 subjects were divided into two groups with 5 pigs induced with pulmonary embolism (Desaive et al. (2005); Ghuysen et al. (2008)). The remaining 4 are induced with septic shock, and treated with haemofiltration starting at two hours (Lambermont et al. (2003)). Both studies were under the control of the ethics committee of the medical faculty of Liege, Belgium.

In all subjects, except one, measurements were taken every 30 minutes for the duration of the trial. The exception was a 60 minute interval for one pig induced with septic shock. At each measurement interval a single representative heart beat was selected, resulting in 51 heart beats for the pulmonary embolism group, and 34 for the septic shock group. In each case the following relevant measurements were taken: aortic pressure ($P_{ao}$), pulmonary artery pressure ($P_{pa}$), left and right ventricle volume ($V_{lv}$, $V_{rv}$, left and right ventricle pressure ($P_{lv}$, $P_{rv}$). Both the aortic and pulmonary artery pressure were measured using catheters, with the right and left ventricle pressure and volume were directly measured using 7F, 12 electrode conductance micro manometer tipped catheters.

The captured data includes the whole range of each dysfunction from healthy to the fully developed disease state. Thus, it provides a good set of data to watch to progression of the disease state. For details see (Desaive et al. (2005); Ghuysen et al. (2008); Lambermont et al. (2003)).

### *2.1 Time-varying cardiac elastance*

From the data gathered, an approximation of the time-varying cardiac elastance ($e_{lv}$) was calculated. The pressure waveforms were processed to find the location of specific features (Stevenson et al. (a)). Once these locations are known, a continuous time-varying cardiac elastance can be constructed that very closely approximates the invasively measured cardiac elastance (Stevenson et al. (b)). This approximation is achieved through correlations that map the points on the pressure waveforms to points on the cardiac elastance waveform, through which a continuous curve can be drawn. The points on the aortic pressure waveform and a high level view of this method is shown in Figure 1.

### *2.2 Dysfunction markers*

The three properties, afterload ($AL$), systemic vascular resistance ($R_{sys}$) and pulmonary artery resistance ($R_{pul}$), change with both septic shock and pulmonary embolism. However, none of these metrics are known or directly and easily measurable in an intensive care setting. The real values for these metrics were calculated from the pressure waveforms.

Afterload (AL) was determined as the slope on the pressure-volume (PV) loop from the point of end-diastole (mapped vertically down to the abscissa) to the point of end-systole. Both end-diastole and end-systole were located from the crossing points of the left ventricle and aortic pressure waveforms.

The value for $R_{pul}$ is defined using a model-based measure (Starfinger et al. (2008)):

$$R_{pul} = \int_{t=0}^{period} \frac{P_{pa} - P_{pu}}{Q_{pul}} \mathrm{d}t \tag{1}$$

where, $P_{pu}$ is the pressure in the pulmonary vein, $Q_{pul}$ is the flow through the pulmonary artery, and thus the integral of $Q_{pul}$ over one heart beat is the right stroke volume (RSV). The pulmonary vein pressure was not measured in the porcine cohort, and as an approximation has been set to 0. Thus $R_{pul}$ becomes:

$$R_{pul} = \frac{1}{RSV} \cdot \int_{t=0}^{period} P_{pa}(t)\ \mathrm{d}t \tag{2}$$

This approximation should capture all necessary trends for this analysis.

$R_{sys}$ is defined in a similar way to $R_{pul}$ (Starfinger et al. (2008):

$$R_{sys} = \int_{t=0}^{period} \frac{P_{ao} - P_{vc}}{Q_{sys}} \mathrm{d}t \tag{3}$$

where, $P_{vc}$ is the pressure in the vena cava, $Q_{sys}$ is the flow through the aorta, and thus the integral of $Q_{sys}$ over one heart beat is the left stroke volume (LSV). The vena cava pressure is calculated as the pressure in the right ventricle at the time of end-systole. Thus, $R_{sys}$ becomes:

$$R_{sys} = \frac{1}{LSV} \cdot \int_{t=0}^{period} P_{ao}(t) - P_{rv}(\text{end-systole})\ \mathrm{d}t \tag{4}$$

A grid search was run over all combinations of correlations between these three parameters and any other property which is known to be available in an intensive care unit.

## 3. RESULTS

### *3.1 Afterload (AL)*

From the grid search results for afterload, the following was chosen as it shows very good accuracy in tracking afterload in the septic shock cohort:

$$\frac{AL}{GEDV} \propto \frac{\int_{t=0}^{period} P_{ao}\ \mathrm{d}t}{LSV \cdot \text{end-systole}_t} \tag{5}$$

where $GEDV$ is the global end-diastolic volume, calculated as the sum of the maximum left and right ventricle volumes.

The approximation of afterload is thus:

$$AL_{approx} = C_1 + C_2 \cdot \frac{\int_{t=0}^{period} P_{ao}\,\mathrm{d}t}{LSV \cdot \text{end-systole}_t} \tag{6}$$

where:

$$\begin{aligned} C_1 &= GEDV \cdot C \\ C_2 &= GEDV \cdot m \end{aligned} \tag{7}$$

and $C$ and $m$ are the coefficients of the correlation, and are defined in Table 1. The results of the correlation and the estimation errors are shown in Table 2.

Figures 2 - 3 show the correlations and their straight line estimators from Table 1 for the pulmonary embolism and septic shock cohort respectively. The estimations for afterload and shown in Figures 4 - 5, for each subject individually.

### *3.2 $R_{sys}$*

The correlation that produced the best results for $R_{sys}$ was found to be:

$$\frac{R_{sys}}{period} \propto \frac{P_{ao}(DMPG)}{LSV} \tag{8}$$

where $DMPG$ is defined in Figure 1.

Thus, the approximation of $R_{sys}$ is:

$$R_{sys,approx} = C_1 + C_2 \cdot \frac{P_{ao}(DMPG)}{LSV} \tag{9}$$

where

$$\begin{aligned} C_1 &= period \cdot C \\ C_2 &= period \cdot m \end{aligned} \tag{10}$$

and $C$ and $m$ are the coefficients of the correlation, and are defined in Table 1, and the results of the correlation and the estimation errors are shown in Table 3.

Figures 6 - 7 show the correlations and their straight line estimators from Table 1 for the pulmonary embolism and septic shock cohort respectively. The estimations for afterload and shown in Figures 8 - 9, for each subject individually.

### *3.3 $R_{pul}$*

The correlation that produced the best results for $R_{pul}$ was found to be:

$$\frac{R_{pul}}{period^2} \propto \frac{e_{lv}(MPG)}{RSV \cdot period} \tag{11}$$

where $MPG$ is defined in Figure 1.

Thus, the approximation of $R_{pul}$ is:

$$R_{pul,approx} = C_1 + C_2 \cdot \frac{e_{lv}(MPG)}{RSV \cdot period} \tag{12}$$

where

$$\begin{aligned} C_1 &= period^2 \cdot C \\ C_2 &= period^2 \cdot m \end{aligned} \tag{13}$$

and $C$ and $m$ are the coefficients of the correlation, and are defined in Table 1, and the results of the correlation and the estimation errors are shown in Table 4.

Figures 10 - 11 show the correlations and their straight line estimators from Table 1 for the pulmonary embolism and septic shock cohort respectively. The estimations for afterload and shown in Figures 12 - 13, for each subject individually.

Table 1. The results of the two correlations, showing the $R^2$ value along with the straight line coefficients that are used in the approximation

| Correlation | $C$ | $m$ |
|---|---|---|
| Afterload | 0.543 | 0.00745 |
| $R_{sys}$ | -0.0418 | 0.973 |
| $R_{pul}$ | -0.0958 | 74.4 |

Table 2. Afterload: Correlation and median percentage error for estimating afterload

| | Pulmonary Embolism | Septic Shock |
|---|---|---|
| $R^2$ | 0.543 | 0.883 |
| Error | 21.56% | 11.82% |

Table 3. $R_{sys}$: Correlation and median percentage error for estimating systemic vascular resistance $R_{sys}$

| | Pulmonary Embolism | Septic Shock |
|---|---|---|
| $R^2$ | 0.508 | 0.904 |
| Error | 12.51% | 13.50% |

Table 4. $R_{pul}$: Correlation and median percentage error for estimating pulmonary vascular resistance $R_{pul}$

| | Pulmonary Embolism | Septic Shock |
|---|---|---|
| $R^2$ | 0.860 | 0.705 |
| Error | 12.16% | 44.51% |

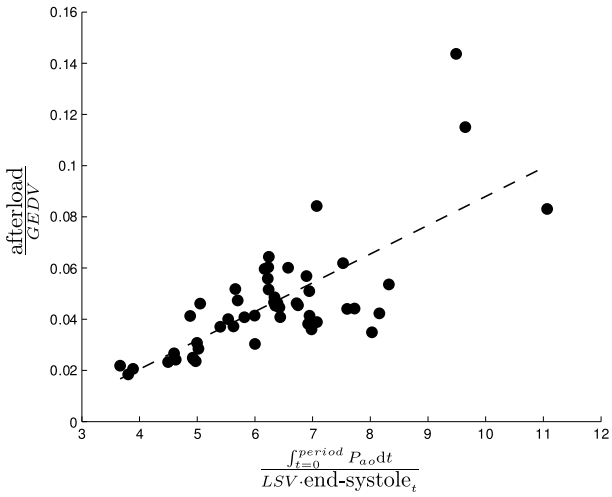


Fig. 2. The correlation for estimating afterload in the pulmonary embolism cohort

## 4. DISCUSSION

The results presented in this paper, generally provide a excellent accuracy for the estimation of afterload, $R_{sys}$ and $R_{pul}$. It should be noted that all three correlations require a side specific stroke volume. In most cases, the left and right stroke volume should be the same or very similar in which case $RSV$ and $LSV$ could be replaced with a more generic stroke volume that is available in the ICU. However, the subjects in this trial showed significant

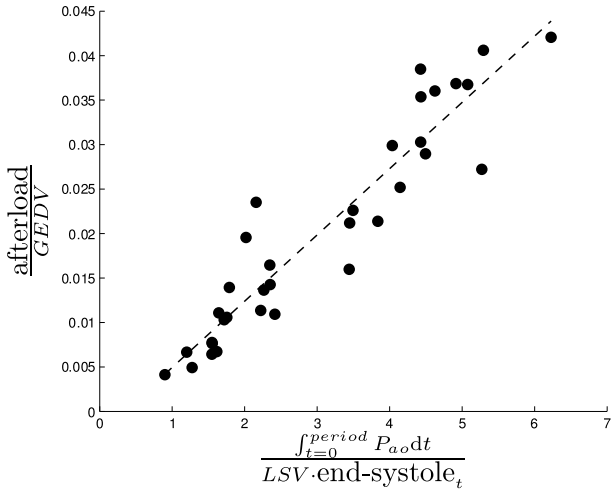


Fig. 3. The correlation for estimating afterload in the septic shock cohort

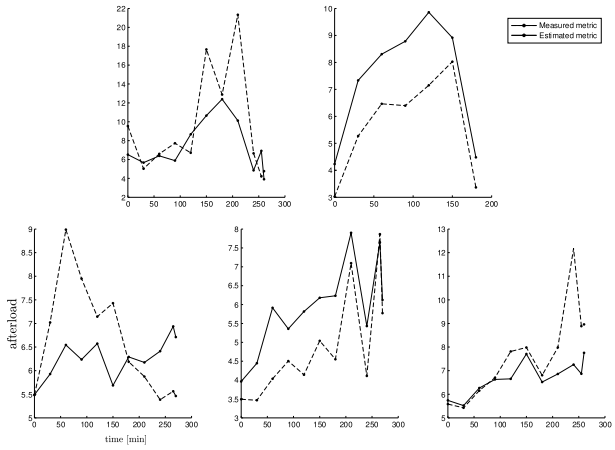


Fig. 4. Estimating afterload on the pulmonary embolism cohort

differences between the two stroke volumes and hence for this presentation they have been kept separate.

The correlations presented in this paper were chosen as those that best matched the most critical dysfunction while still being able to match the trends for the other. Both afterload and $R_{sys}$ are more of a indicator for sepsis, and hence the correlation that best matched sepsis held more weight over those that best matched pulmonary embolism. Most importantly, a distinction can be made between the two disease states from the estimations shown. A sharp drop is clearly visible in all the septic shock subjects in both afterload and $R_{sys}$, and none of the pulmonary embolism subjects. It could then be assumed, that if this sharp drop is seen, the subject is a better candidate for a septic shock diagnosis.

The parameter $R_{pul}$ is more important for the pulmonary embolism diagnosis, and hence the correlation for this was chosen with more importance placed on the accuracy of the pulmonary embolism estimation over septic shock. For the pulmonary embolism cohort, a steady but significant increase in the estimated $R_{pul}$ is observed, while for the septic shock cohort, $R_{pul}$ averages out to steady or a slight decline.

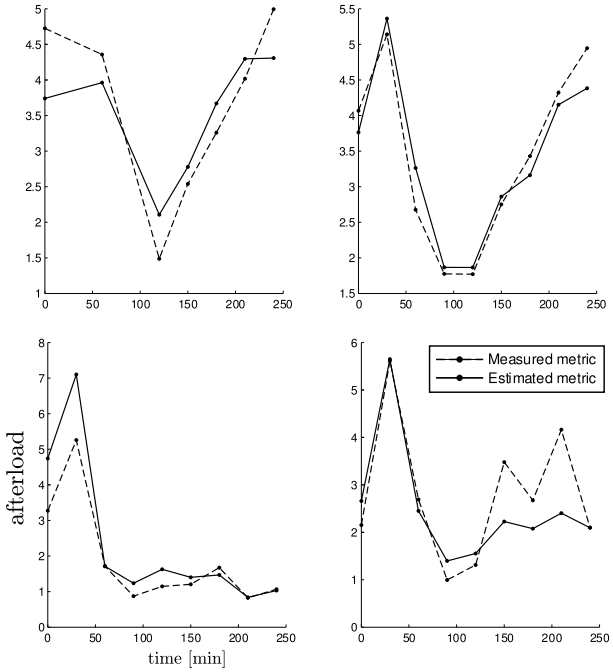


Fig. 5. Estimating afterload on the septic shock cohort

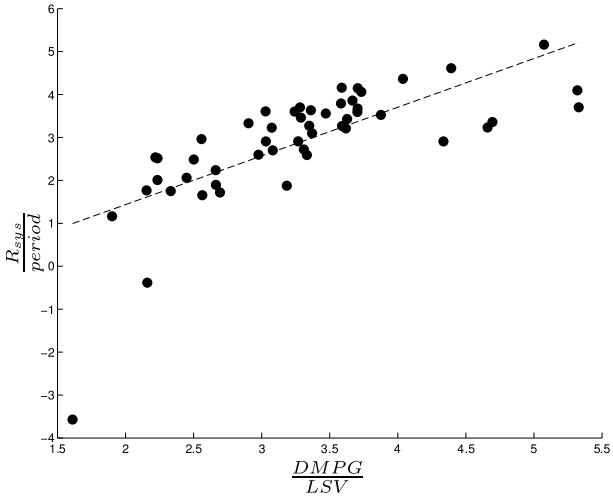


Fig. 6. The correlation for estimating $R_{sys}$ in the pulmonary embolism cohort

The three parameter estimations presented in the paper are all very useful metrics to have access to as a clinician, for both diagnosis and management. For example, if $R_{sys}$ is tracked in real time, this would enable accurate determination of when vasopressor therapy should begin, and based on responsiveness to that therapy, $R_{sys}$ could help optimise dosage.

The main effect for the both these metrics is their relative change over time, and this behaviour is captured very well in almost all cases, with only two exceptions. The first is the third subject for afterload in the pulmonary embolism cohort and the fourth subject for $R_{pul}$, again in the pulmonary embolism cohort.

The diagnostic value of this information is seen when comparing the two cardiac dysfunctions, and the relative trend lines for both parameters. In pulmonary embolism,

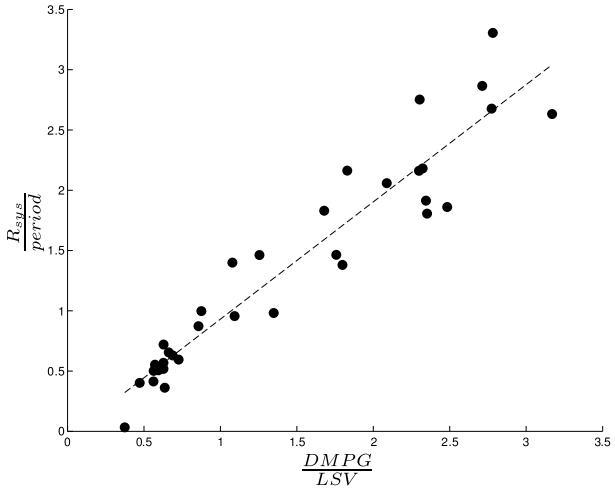


Fig. 7. The correlation for estimating $R_{sys}$ in the septic shock cohort

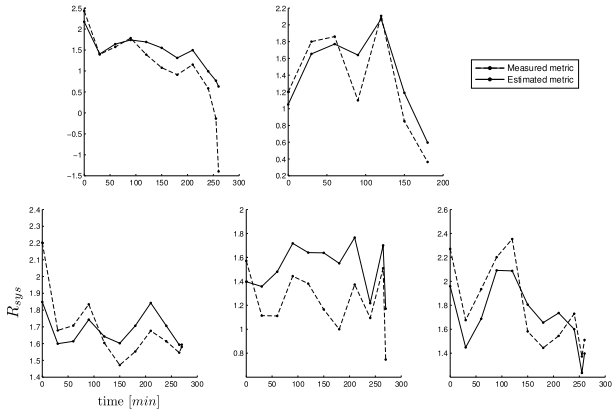


Fig. 8. Estimating $R_{sys}$ on the pulmonary embolism cohort

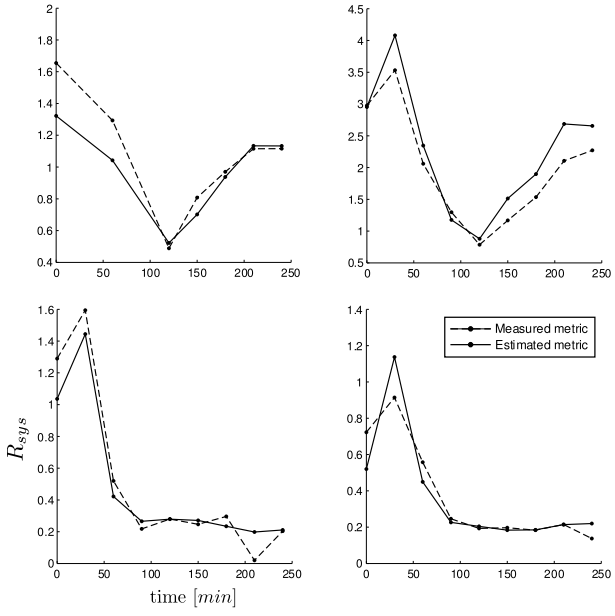


Fig. 9. Estimating $R_{sys}$ on the septic shock cohort

$R_{pul}$ will increase, due to the obstruction in the pulmonary artery. However, $R_{pul}$ also increases in septic shock, usually at a lower rate. Given the results in this paper, $R_{pul}$

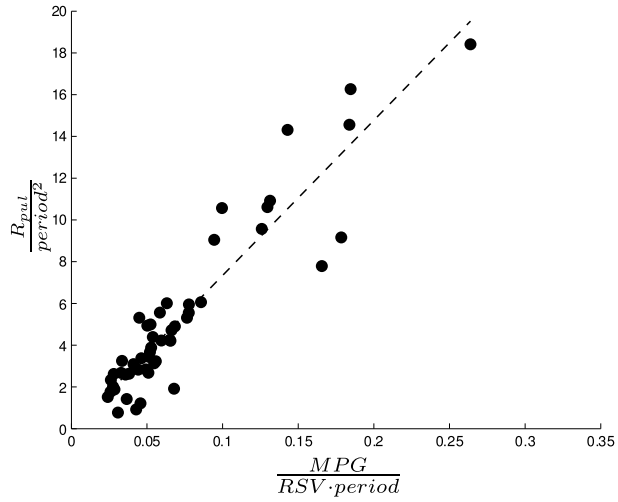


Fig. 10. The correlation for estimating $R_{pul}$ in the pulmonary embolism cohort

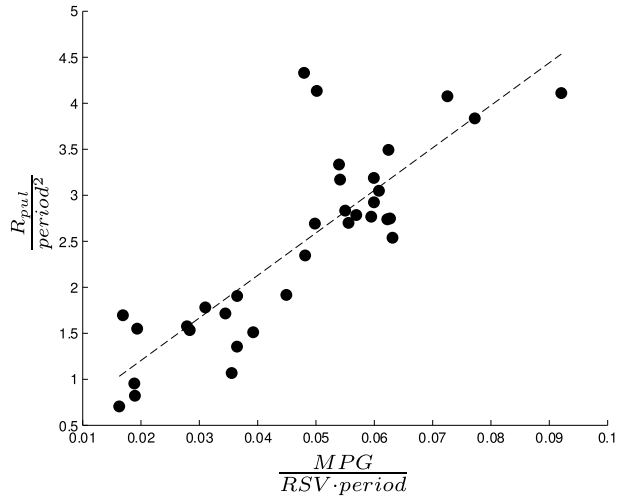


Fig. 11. The correlation for estimating $R_{pul}$ in the septic shock cohort

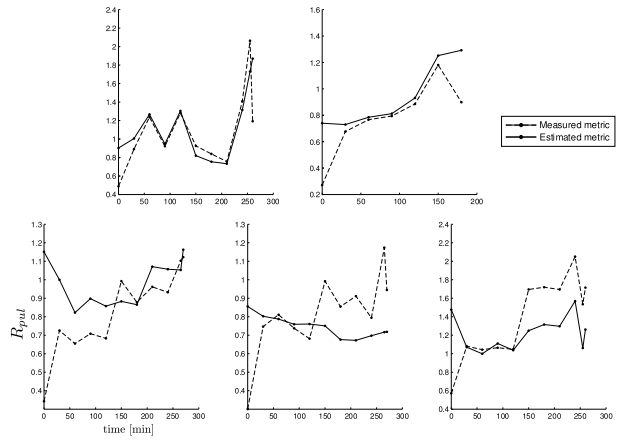


Fig. 12. Estimating $R_{pul}$ on the pulmonary embolism cohort

does increase more for pulmonary embolism, but not by a significant margin. It is only when you combine $R_{pul}$ with afterload and $R_{sys}$ that the distinction can be clearly made between the two cardiac dysfunctions. For the septic shock

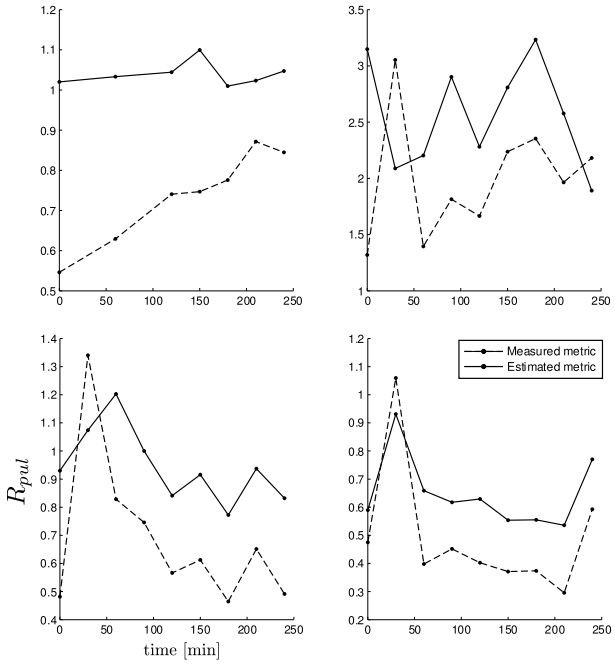


Fig. 13. Estimating $R_{pul}$ on the septic shock cohort

subjects, both afterload and $R_{sys}$ show rapid decreases in the early stages, after which they both level off. This recovery is most likely due to the effects of haemofiltration. Compared to this initial drop in afterload and $R_{sys}$ for septic shock, pulmonary embolism shows gradual for distinct rise, most notable absent of the initial drop.

## 5. CONCLUSIONS

This paper has presented a method to estimate afterload, systemic vascular resistance and pulmonary vascular resistance, using measurements that are commonly known in an intensive care setting. These estimations are accurate in their relative trends, and can give useful addition information to the diagnosis and management of pulmonary embolism and septic shock.

A larger cohort would be needed to validate this study. However, the results presented demonstrate the use of non additionally invasive metrics to extract useful information that would otherwise be unknown to and intensive care clinician, increasing the value of catheters.

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